FINAL TECHNICAL REPORT

COMBUSTION INSTABILITY IN LIQUID PROPELLANT ROCKET MOTORS

Research Supported Under
NASA Grant No. NGR 31-001-155

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December 1974

AMS Report No. 1203

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ABSTRACT

This final report on combustion instability in liquid rocket motors summarizes the work of recent years conducted at Princeton University. Reference is made to the early, broader scope of this research, but the report concentrates on three (more recent) topic areas: (1) acoustic damping devices to control combustion instability, (2) the mechanism of unsteady combustion studied as jet and wakes simulating droplet burning conditions and (3) experimental and theoretical investigations of the mixing processes associated with rocket combustion. The details on any of these topics will require the reader to consult the referenced reports and papers.

I. Introduction

Results from the nation's research programs dealing with combustion instability associated with liquid rocket engine development has added to the knowledge in a variety of subject areas associated with this engineering problem. The range of topics cover those of a basic and scientific nature and extend to the most applied.

Research on liquid rocket combustion instability has been conducted at Princeton University since the pioneering work of Prof. Luigi Crocco in 1951 and with support from a number of government agencies. The results from that research has reached the "rocket community" through numerous progress and annual reports and presentations at the annual JANNAF working groups on combustion. In recent years the complete details are found in Ph.D. theses in the Aerospace and Mechanical Sciences Department. The other principal mechanism for conveying these findings has been papers in technical journals in the United States and abroad and the Reference Book(1). A complete listing of all of these publications appears in the attached bibliography.

Table 1 summarizes the extent and variety of the research activities in combustion instability as conducted at Princeton in the late 1960's. In the succeeding years the topic areas have become more specialized with concentration on: acoustic damping devices to control combustion instability, the mechanism of unsteady combustion studied as jets or wakes simulating droplet burning conditions; and experimental and theoretical investigations of the mixing processes associated with rocket combustion.

The following report summarizes the content of the later years of this research hopefully guiding the reader to studies which will convey knowledge pertinent to ongoing activities.

II. Acoustic Damping Devices

Acoustic liners for use in the suppression of high frequency combustion instability is treated in Princeton references covered over a number of years,[2-5 , 6* and 7]. Reference is first made to the Ph.D. thesis of Dr. Thomas Tonon.

In the Tonon report[7] the past theoretical approaches to acoustic liner designs are reviewed. The report points out that there is significant interaction between the lined surfaces and the combustion conditions present in actual combustors. However, the analysis in the report is for the uncoupled liner problem as a first step toward the coupled solution. The flow field associated with typical liners is described mathematically, tying these concepts together with physical concepts valuable to both experimental and theoretical endeavors. The report focuses on analytically studying the liner response including: the chamber velocity (both mean and oscillatory), chamber pressure effects, a steady mean flow through the liner, a steady fluid motion in the liner backing volume (cavity) and a very slight difference

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* This Master's Thesis covered the topic of nonsinusoidal pressure oscillation on Helmholtz resonator behavior.

between the temperature in the chamber and that in the backing volume. The study was valid for near-resonance oscillations, retaining the first harmonics of the first order solution. The first order solution thus obtained is formally correct only in special cases. However, in other cases such simplification should still provide results accurate enough for practical computation of liner solutions -- typical damping problems are covered. Off-resonance solutions are discussed with regard to chamber velocity and pressure effects. Effects of large differences in mean temperature, molecular weight and the ratio of specific heats between liner cavity and chamber are also treated in this report[7], but cases are considered only when the fluid motion through the liner is quasi-steady. Design implications, boundary influences of the liner, and liner response are covered in turn. The rationale for certain design procedures together with overall conclusions are presented.

The principal conclusion of the Tonon report is that in relatively high amplitude regimes of flow through the liner orifices, such flow is jet-like. The mechanism for energy dissipation is the conversion of jet kinetic energy into a more random form of mean internal energy. Orifice resistance is expressed accordingly. The true nonlinear resistance depends on time, rather than the quantity commonly used in the literature, which should be called equivalent-linear resistance or effective-linear resistance.

The solutions to the damping problems require the input of the correct geometrical factors since the method described applies to Helmholtz; quarter, half wave or multiple dimension damping device configurations. The quarter-wave geometry accomplishes the maximum damping for a limited volume.

In Helmholtz resonator applications, where appreciable differences exist between chamber and cavity, a mean orifice velocity must be employed in the solution.

Cross-flow over the orifices contributes to the local effective pressure increasing the liner orifice motion above the norm. The true forcing function, "equivalent pressure," is a function of both external pressure and cross flow; however, the time average of the product of equivalent pressure and velocity does not equal the actual liner dissipation.

The primary function of the liner is to dissipate energy, hence optimum performance is sought by maximizing the real part of the liner's admittance. Procedures to achieve this goal with minimal liner material are outlined in the report with attention given to the modes of instability likely to be encountered in a practical combustor geometry.

The companion report to the theoretical study just discussed is the Ph.D. thesis of Dr. P. K. Tang[10] companion publications[(8-9),(11-12)]. Here the emphasis is in evaluating a variety of solutions to damp combustion instability oscillations using mechanical devices. The theory of the quarter-wave tube is treated for both off-resonance and near-resonance operation, the proper introduction of the boundary conditions and computations for designing this damping device are covered. Helmholtz resonator calculations are approached in a similar manner. Finally the so-called "long damping device", a family of geometrical variations on the quarter-wave tube and Helmholtz resonator theme (e.g., 3/4 wave length tube or a long orifice with an extended volume chamber tuned to damp a given frequency), is analyzed.

Each of these devices was evaluated in a test facility which was capable of varying frequency, amplitude, pressure and cross velocity for the damping device under study. Operation at pressure and velocity node and antinode locations was checked. The damping devices themselves could be geometrically altered during tests. Quartz Kistler pressure transducers were placed in both the test duct and the damping devices. Velocities were measured with two hot wire probes and associated electronics.

The conclusions of the report emphasize the close agreement between the developed theories and experiments. Only in the special case where internal friction losses became a factor -- a parameter not accounted for in the case of a long tube, - - was there divergence between theory and experiment. This broad survey of various damping devices for a given application allows the designer a wide latitude of choice. Emphasis is placed on the merits of different design approaches, e.g., the damping efficiency of the quarter wave tube but the narrow range of frequency variation it can handle - - the contrasting broader range of frequency covered by the short orifice Helmholtz resonator. Charts are presented which compare the important design parameters to speed the task of choosing the proper damping device for a given application.

III. Unsteady Combustion Studied as Jets or Wakes Simulating Droplet Burning Conditions

A second topic of concentration in recent years has been that of jets or wakes as simulating droplet burning conditions. This subject has been treated in a number of Princeton references [13-18]. Dr. Ashok Varma in his Ph.D. thesis focused his attention on "Interaction of Reacting and Non-Reacting Flows with a Coaxial Oscillating Stream in the Near Region". The report studies the effect of axial velocity oscillations imposed at the boundaries of both axisymmetric cold flows and diffusion flame flow fields are studied in detail. A linearized theoretical analysis of the near region of the flow field is presented and a comparison of the experimental measurements to the numerical theoretical solution is shown. The nonreacting flow velocity measurements are made with the aid of hot wire probes. Temperature measurements in the flames are made with coated fine-wire thermocouples. It is shown that the imposed oscillations interact significantlv with the flow field, resulting in amplification of the oscillations and large phase changes. The interaction depends strongly on the frequency and axial position, and reaches a maximum when the wave travel time is of the same order as the diffusion time across the shear layer. The product of the frequency and the axial position for maximum interaction is shown to be a constant. The amplitude of the imposed oscillations also affects the nature of the interaction, with moderate amplitude oscillations (25% rms) causing significant changes in the mean flow structure corresponding to increased mixing and burning rates, a shorter potential core region and a shorter mean flame length.

The theoretical model is used to calculate the mass burning rate perturbations in the wake flame of a fuel droplet during longitudinal combustion instability conditions in a liquid propellant rocket motor. The theory predicts large magnitude burning rate response in the frequency range of interest for combustion instability, but the response is shown to be stabilizing in nature for the presence of fundamental standing wave instability oscillations.

The externally imposed finite amplitude oscillations interact significantly with the mixing processes in the near field of two nonreacting coaxial streams. The amplitude of the external oscillations may be amplified by 100% or more in the shear layer region. The interaction is a strong function of the frequency and the axial location downstream of the exit plane of the streams. The experimental measurements are in agreement with the theoretical predictions that the interaction should be a maximum when the diffusion time across the mixing layer is of the order of the wave travel time. As shown in Chapter II,[18] this leads to the condition that the peak interaction point should follow fX=constant, which condition the experimental data satisfies very well. Even moderate amplitude oscillations (10% rms) cause nonlinear changes in the mean flow structure, which are demonstrated by an earlier breakup of the potential core length compared to the steady state.

The externally imposed finite amplitude oscillations interact significantly with the mixing and combustion processes of a diffusion flame flowfield. The interaction is a strong function of the frequency and axial location downstream of the exit plane of the burner. The response exhibits a maximum at a certain critical frequency ($\sim$ 14 Hz for the 1/2 inch burner and the flow parameters used in the current experiments). The interaction begins in the near field region close to the burner exit, and leads to a decrease in the mean flame length and increase in the mean flame width. The measurements show that there are large amplitude temperature fluctuations in the flow field and the imposed oscillations cause significant changes in the mean temperature profile.

In applying the findings to the case of longitudinal combustion instability, considering a traveling longitudinal wave, pressure and velocity perturbations phase is such that the unsteady mass release has a destabilizing effect at every point in the chamber. Thus, for higher harmonic standing wave oscillations and for travelling waves, the wake flame response could be an important combustion instability mechanism, due to the large magnitude of the response in the frequency range of interest. However, longitudinal combustion instability oscillations in the fundamental standing mode are generally the most likely to occur for a given rocket engine system, and for these, the results of the study of the response of the near-field of the droplet wake flame region are negative, that is, the response is stabilizing and cannot provide the feedback necessary to sustain the combustion instability oscillations. The result is somewhat disappointing, but is in agreement with the practical experience, that most currently used liquid propellant rocket engines are not subject to longitudinal combustion instability oscillations, but instead are prone to transverse combustion instability. The theory presented here(18) cannot be directly extended to study transverse oscillations.

A more complete study of the entire wake flame region (near, intermediate, and far-field) is presently being carried out at Princeton which will be able to avoid some of the assumptions (and limitations) of the previous investigations. The results of this analysis should provide conclusive proof as to whether the response of the wake region of the droplet, in combination with the response functions for other regions of the droplet, provides feedback which is sufficient in magnitude and phase to drive longitudinal combustion instability oscillations in liquid propellant rocket motors.

This phase of the research is being conducted by Mr. Claudio Bruno with a PhD thesis available in winter 1975. The theoretical approach analyzes the effect of the velocity wave on a single fuel droplet, that is assumed to move at a certain relative velocity with respect to the vaporized oxidizer.[19,20]

The physical modeling relies on the well-known finding that, under liquid rocket chamber conditions, a substantial amount of the fuel vaporizing from the droplet is not burned in the upstream portion of the droplet, and is convected instead, inside the wake downstream. Under typical operating conditions this suggests that a diffusion-controlled wake flame ensues, and that, when the period of the velocity wave is of the same order of the diffusion time across the mixing layer, a significant interaction may occur.

In the mathematical model a laminar boundary-layer treatment of the conservation equations is performed; it is found that, for an important fraction of the parameters of interest range, this is indeed justified, and, in particular, that no recirculation cells are likely to exist in the droplet near wake region. A further practical reason for the boundary-layer approach is, of course, the amount of computation required, far less than if the full Navier-Stokes equations were used.

Simple one-step, finite-rate chemical kinetics is employed in the system of equations; to reduce their complexity each of the five main dependent variables is assumed to be composed of a mean and an oscillatory part, which is small with respect to the mean and of the same order of the velocity fluctuations carried by the wave.

The system of equations is then time-averaged and the second-order terms neglected; this uncouples the nonlinear equations for the mean quantities from the linearized equations for the perturbations. Once the former are solved, the latter may be solved too.

The results of the mean equations confirm that the region where the chemical kinetics is important is indeed thin compared to the diffusion region. A correlation is found between the potential core length and the Reynolds, Prandtl and fuel/oxidizer momentum ratio numbers. Except for the case of very low Reynolds No. (or momentum ratio), the total flame length that the theory points to is found to be much larger than typical droplet spacings in the spray portion near to the injector plane region, an indication that droplet wake flames very likely interact with each other.

IV. The Mixing Process Associated with Rocket Combustion

The final phase of combustion instability research that we have concentrated upon these past few years is the important topic of mixing and how it relates to combustion in rockets and similar combustors.[21-23] In the PhD thesis of Dr. Thomas Rosfjord[22] this topic is probed experimentally and theoretically.

The recirculating flow region existing between two jets has been investigated. In particular, the effect of various degrees of inlet asymmetry on the fluid dynamic structure, both for a reacting and non-reacting flow, was studied. The fluid jets were physically identical and emerged from a slot injector separated by nine jet widths. Both experimental and theoretical investigations were conducted. The experimental tasks included the probing of the recirculation region of a combusting flow of $H_2/O_2/N_2$. The determination of the flow structure response to an asymmetric inlet condition was obtained by employing a tracer bubble visualization technique to an hydraulic simulation of the combusting system. Numerical solutions to the governing system of elliptic, partial differential equations were obtained by employing the techniques developed by D. B. Spalding, et. al. Several prominent observations and conclusions can be presented:

1. The envelope of recirculating flow for non-combusting systems extended one jet separation downstream from the injector face. The corresponding region for a combusting flow extended half as far downstream. This response is due to the presence of the high temperatures associated with the combustion process. The accompanying decreased density resulted in an increased momentum diffusivity (μ/ρ). The increased diffusivity promoted an increase in the jet interaction and ultimately results in a shortened zone of recirculating flow.

2. A symmetric flow pattern, for a symmetric inlet condition (i.e. equal jet strengths), was observed both experimentally and theoretically. Asymmetric inlet conditions resulted in at least a partial entrainment of the weaker jet. Numerical solutions of a multi-specie flow indicated that the relative jet strength is determined by the ratio of inlet jet momentum. flux, MOMR. A total entrainment of the weaker jet occurred for MOMR $\geq$ 2.0. The fraction captured decreased linearly with MOMR to a zero value for the truly symmetric flow pattern.

This changing flow structure also resulted in the shift of location of the intense energy release for a combusting flow. This region shifted monotonically toward the stronger inlet jet as its relative jet strength increased.

3. For cold flows, the mixing of injected species increased with inlet asymmetry. At one jet spacing downstream, approximately the end of the recirculating patterns, a value MOMR= 0.42 resulted in an 18% root mean square (RMS) non-uniformity of the injected species. For MOMR=0.59, RMS=44% and for MOMR= 1.00, RMS=55%. This variation can be attributed solely to the response of the flow structure; the diffusional transport of mass was identical for each case. The distinction in non-uniformity for the several inlet asymmetries further downstream was eroded because of diffusional transport. All cases considered demonstrated RMS 10% by three jet spacings downstream.

It appears, however, that the prescription of a single value of each transport property uniformly over the entire flow region is not sufficient for two jet mixing problems such as considered in this study. In particular, the use of only the effective viscosity value representative of the recirculating flow region appears to greatly overstate the property transport downstream of this region.

4. For combusting flows, the spatial rate of propellant consumption was equivalent for different inlet asymmetries. Sixty-four percent of the injected propellant was consumed within one jet spacing; 84% and 92% was consumed by two and three spacings, respectively.

5. External influences, such as the presence of side walls,

can affect the downstream flow patterns but were not observed to alter the basic fluid dynamic structure within one jet separation of the injector. These influences promoted a fluid dynamic stall similar to one that might be observed in a subsonic diffuser. The associated flow pattern can be as complex as the recirculating flow region of interest in this study. For practical systems such a pattern may or may not be desirable. From a mixing point of view, such occurences can be beneficial. However the associated features of increased pressure loss and heat transfer through the walls could be detrimental. Therefore all features of a particular flow pattern must be considered in the design of a practical system.

V. Comments

Clearly all the detailed information necessary for an adequate understanding of combustion instability as it pertains to combustion devices in general has yet to be obtained through research. Current funding in the liquid combustion instability field is such that progress toward that better understanding has been reduced to a slow pace indeed. Programs in solid propellant combustion research would appear to be progressing more rapidly at present although the future is unclear.

In the final report presented here, some of the most recent findings of the combustion instability research conducted at Princeton have been described. Our group is continuing to study energy-related problems but our topics now are wide spread and include such diverse subjects as fire spreading, stratified engine modeling, residential energy consumption, fabric flammability, fire safety, home appliance efficiency optimization, fundamental combustion studies in I.C. engines, pollution problems related to the character of combustion, etc. We retain our long term interest in finding further answers to the questions that remain in the combustion instability field and are grateful for the continued governmental support we have received in the past to study this important problem.

TABLE I

TOPICS RELATED TO COMBUSTION INSTABILITY IN LIQUID ROCKETS EMPHASIZING MECHANISMS FOR NONLINEAR INSTABILITY ERA 1962 - 1970

- Nonlinear Transverse Instability in Liquid Propellant Rocket Engines
- Longitudinal Nonlinear Rocket Motor Studies Using the Square Motor
- Vapor Displacement Mechanism in the "Pseudo" Rocket Motor
- Droplet Distribution Studies
- Experimental Techniques for Investigating the Combustion Process
- Damping of Shock-Type Waves
- Higher Mach Number Effects in Longitudinal Instability Theory
- A Study of the Parameters Affecting the Transverse Mode Instability Limits
- Longitudinal Shock Wave Combustion Instability
- Chemical Kinetics as a Driving Mechanism for Liquid Propellant Rocket Combustion Instability
- Unsteady Mass-Energy Source Determined by a Shock Tube Technique
- Calculations on Rocket Combustion Instability with a Droplet Evaporization Model
- Hydrogenation Rocket Feasibility Studies

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